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Acquisition of time-lapse, 6-component, P- and S-wave, crosswell seismic survey with orbital vibrator and of time-lapse VSP for CO₂ injection monitoring

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Summary

Using an orbital vibrator source (2-components), and a 40 level 3-component geophone string, a 6-component crosswell survey was acquired before and after a CO₂ injection in a saline aquifer. Decomposition of the two source components and component rotation of both source and sensors created good separation of P- and S-wave energy allowing independent analysis of travel time and reflectivity. A time-lapse VSP was also acquired.

Introduction

As part of a Department of Energy (DOE) funded project on geologic sequestration of CO₂, a time-lapse crosswell seismic survey was acquired before and after injection of CO₂ into a saline aquifer. The aquifer is in the on shore Gulf of Mexico Frio formation sandstone, near Houston, Tx. Among the goals of this pilot sequestration test are the following:

- 1) Demonstrate that CO₂ can be injected into a brine formation without adverse health, safety, or environmental effects.
- 2) Determine the subsurface distribution of injected CO₂.
- 3) Demonstrate validity of conceptual models.
- 4) Develop experience necessary for the success of large-scale CO₂ injection

The Crosswell and VSP experiments are part of an integrated suite of scientific studies with many contributing institutions including the Texas Bureau of Economic Geology.

Data Acquisition

An 80-level 3-component geophone string, supplied by Paulsson Geophysical was used for the crosswell acquisition and a time-lapse vertical seismic profile (VSP) which was acquired simultaneously. For the Crosswell survey, source and receiver spacing was 1.5 m, with the sources spanning 75 m and the sensors spanning 300 m. Five source 'fans' were acquired to give 1.5 m sensor spacing from the 7.5 m fixed sensor spacing. The crosswell survey was conducted using the injection well (for sensors) and a nearby monitoring well (for source) which is about 30 m offset. Crosswell source locations were centered on the injection interval. The crosswell sensors were also centered on the injection interval, which is the 6-7 m thick, upper C sand in the Frio formation which is at a depth of about 1500 m. Initial analysis of the crosswell data shows

good quality P- and S-wave direct arrivals. Time-lapse tomographic imaging is planned for both P- and S-waves.

The orbital vibrator source is an eccentric mass rotated by an electric motor. The source is fluid coupled to the surrounding formation. The rate of rotation is linearly varied up to 350 Hz and back to stop. Useable energy is acquired above about 70 Hz, giving a 70 to 350 Hz bandwidth. At each source location a clockwise and counter clockwise sweep is recorded. Decomposition of these two sweeps provides two equivalent sources with orthogonal horizontal oscillations (Daley and Cox, 2001). Component rotation using P-wave particle motion rotates these two sources into in-line and cross-line equivalents, with in-line being horizontal and in the plane of the two boreholes (Gritto, et al, 2004). Figure 1 shows a 6-component receiver gather (all source depths for one receiver depth) with in-line and cross-line sources for the vertical and two horizontal receiver components.

The VSP used an 80 level, 3-component geophone string and explosive source. Eight source shot points were acquired. The sensors were interleaved to give spacings of 1.5 to 7.5 m. The shotpoints were offset 100 to 1500 m from the sensor well. The location of the shotpoints was designed to monitor the estimated CO₂ plume location and to provide structural information at the injection site. VSP data have good quality direct and reflected events. Comparison of variable sensor spacing shows advantage of increasing spatial sampling.

Data Analysis

After the two acquired orbital vibrator sweeps (clockwise and counter-clockwise rotation) are decomposed into orthogonal 'x' and 'y' data traces, these traces are numerically rotated into in-line and crossline orientations. The rotation angles were calculated using the P-wave particle motion recorded on one of the sensor components. The angles from each sensor were combined in a weighted average with the weights determined by the particle motion linearity.

For tomography, the travel times were picked using the in-line source for P-wave and the crossline source for S-wave (see Figure 1). Initial results indicate a reduction in velocity, as expected from CO₂ injection.

The initial processing of the VSP has focused on time lapse change in reflection amplitude of the reservoir horizon. An amplitude equalization was applied using a reflection above the reservoir. An initial result from one source location is shown in Figure 2.

Time Lapse Crosswell and VSP for CO2 Monitoring

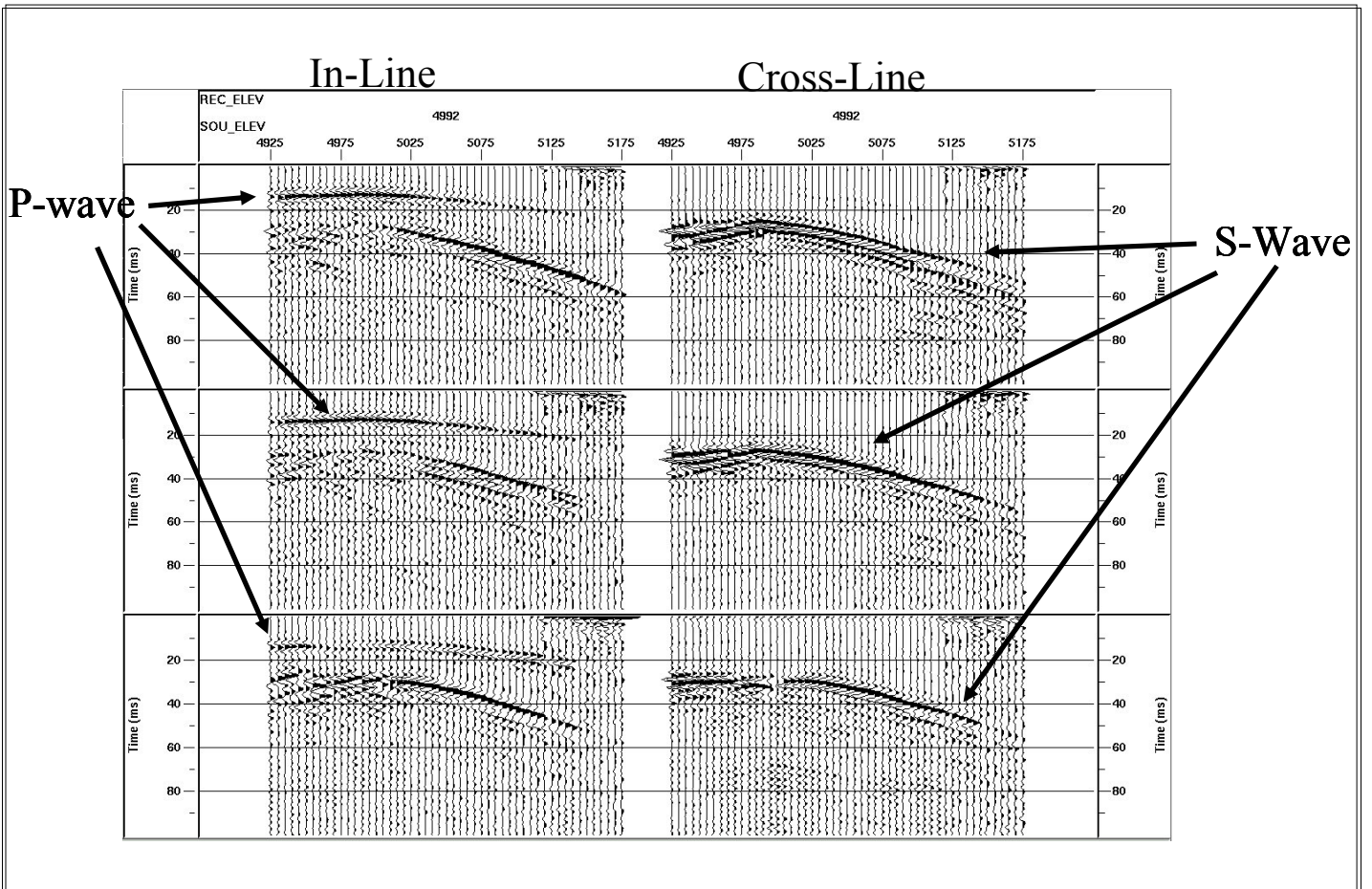


Figure 1: 6-component crosswell receiver gather. The two columns are in-line and cross-line source components. The rows are vertical and two horizontal receiver components (top to bottom). Each trace amplitude is normalized to its own maximum. The cross-line source component shows good separation of S-wave energy (i.e. minimization of P-wave).

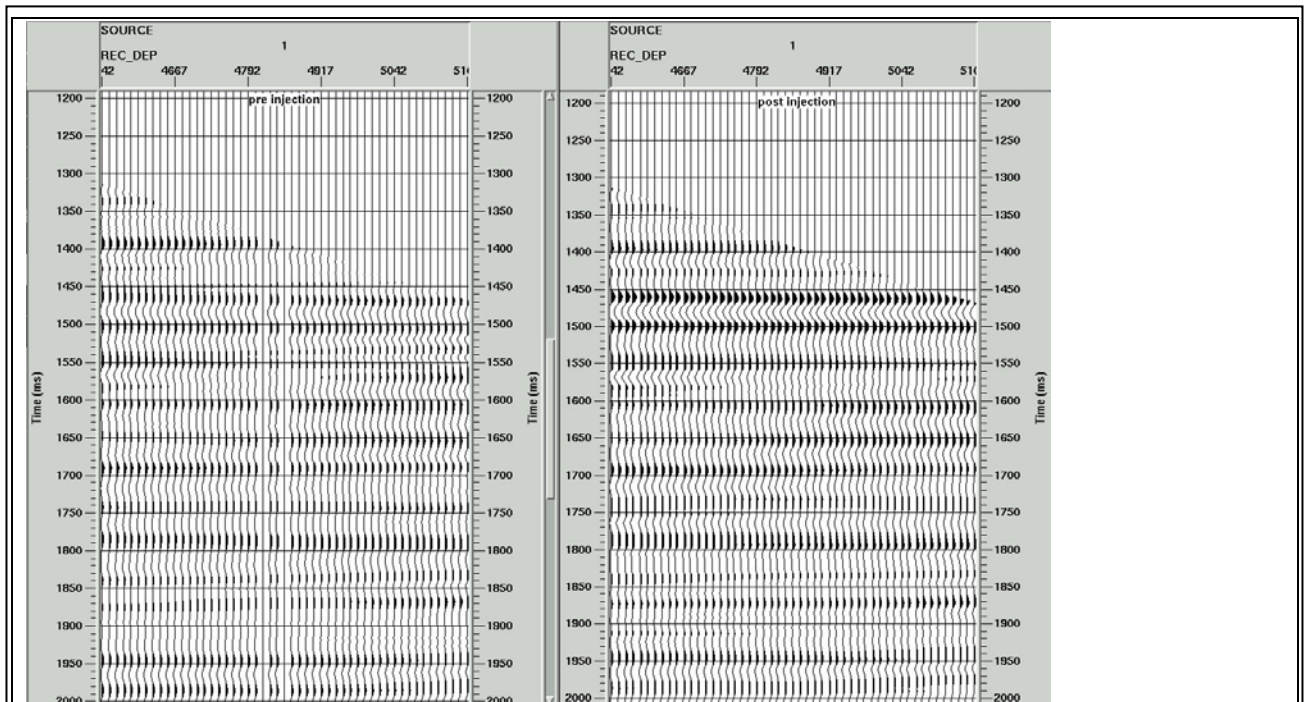


Figure 2 VSP reflection section before (left) and after (right) CO2 injection. An increase in amplitude is seen in the reservoir reflection between 1450 and 1500 ms.

Time Lapse Crosswell and VSP for CO2 Monitoring

Conclusions

Seismic monitoring data has been collected as an integral part of a CO₂ injection experiment. Both VSP and crosswell data were acquired. A massive 80 level 3-component sensor string allowed high spatial sampling over a large depth interval. The use of an orbital vibrator borehole source allowed both P- and S-wave data to be collected. The pre and post injection data is good quality, both for VSP and Crosswell.

Initial analysis of time-lapse crosswell P-wave tomography changes indicate velocity reduction in the reservoir. Initial analysis of VSP time-lapse change indicates an increase in reflection strength.

References

Daley, T. M. and Cox, D., 2001, Orbital vibrator seismic source for simultaneous P- and S-wave crosswell acquisition, *Geophysics*, 66, 1471-1480.

Gritto, R., Daley, T. M. and Myer, L.R., 2004, Joint crosswell and single-well seismic studies of CO₂ injection in an oil reservoir, *Geophysical Prospecting*, 52, 323-339.

Acknowledgments

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